Overview of Rayleigh-Taylor Instability and the Impact on Target Design for a Pulsed Fusion / Fission Propulsion System

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Introduction

- Nuclear propulsion systems have the potential for much higher specific impulse than chemical engines
  - Various concepts have been proposed in the past (NTRs, Orion, etc.)

- If implemented a Fusion based system could way out perform a fission system such as an NTR, but has suffered from technical challenges
  - Confinement at the required density and for the necessary length of time has been difficult to achieve due to plasma instabilities
  - However; a fusion / fission hybrid could relax the confinement requirements
  - Management of the instabilities with mitigating processes could improve confinement

- Interested in the design of a z-pinch target that manages instabilities to achieve fusion / fission reactions for a propulsion system
Rayleigh-Taylor Instability (RTI)

• Most destructive

• Occurs due to acceleration and density gradient vectors in opposite directions
  – Light fluid supports dense fluid

• Small perturbations at interface between fluids quickly grow leading to turbulent mixing
Rayleigh-Taylor Instability (RTI)

• Estimates of growth rates of interest
  – typically calculated with linearized MHD equations
  – Relevant to confinement time

• Interested in cylindrical geometry in which the magnetic field acts as the lighter fluid (density of zero)
  – As in a z-pincho

Schlieren image of z-pincho. Cylindrical geometry disrupted by instabilities

• Image: Ben Dudson, *Plasma Instabilities*, University of York
What is a Z-pinch?

- A z-pinch a large pulsed current with high $\text{d}I/\text{d}t$ to generate an azimuthal magnetic field and ionize the target. The current and magnetic field produce the Lorentz force and compress the target.
- This process is one concept for producing fusion reactions.
- The fusion/fission propulsion system concept of interest uses a z-pinch to compress the fuel.
RTI – Mitigating processes

• Decades of study and experiment have shown various processes to have mitigating effects upon the growth rate of the Rayleigh-Taylor Instability
  – E.g. shock waves, tailored density profiles, staged annular collapse, viscosity, shear, and resistivity

• Past experiments should be well understood and used to guide the development of a target for a z-pinch propulsion system

• Several of the following slides highlight particularly interesting experiments
From Literature - Experiments of Interest
Frozen Deuterium Exploding Wires

• Wires of Frozen Deuterium used in z-pinch experiments
• Unexpected level of stability
  – Loss of stability occurred at max current, $dI/dt=0$, and at complete ablation of wire core
• Expected contributions to stability
  – Sufficient resistivity in plasma
  – Ablation of the wire core
Dielectric coatings have been used to suppress instability development
- Reduces electrothermal instabilities at the surface which seed RTI
- Reduced initial perturbations lead to reduced RTI growth

X-Ray images to the right show large improvement in stability for coated surface
• Largest growth rates occur when wave number and magnetic field are perpendicular

• An axial magnetic field in the z-pinch of a liner with a pre-ionized gas fill can increase stability
  – Magnetic field compresses along with liner

• Radiographs show improved stability for higher axial magnetic field in the image to the right
Pulsed Fusion Fission Propulsion System Concept (PuFF)

- Concept uses a z-pinch to compress the target and burn the fuel through fusion and fission reactions
  - Using a hybrid reaction is intended to relax the conditions under which the plasma must be compressed
- After compression the products are expanded through a magnetic nozzle to produce thrust
- As is the case for other z-pinch applications, RTI is an obstacle
  - Must be managed to achieve successful compression and reaction
  - Stabilizing processes from other experiments may be incorporated into the target design to improve stability and performance
Stability Concepts for Target Design

• Frozen Deuterium/Uranium Pellet
  – A cylindrical pellet with a frozen deuterium core and Uranium shell
    • Frozen core and the ablation process may be stabilizing
    – Frozen deuterium or other dielectric outer coating may be used to suppress electrothermal instabilities to further increase stability

• Uranium liner with Deuterium Plasma fill and Axial B-field
  – Such a concept may employ the stabilizing effect of an axial magnetic field
  – Dielectric coating may also be used to suppress instability development

• Staged Collapse of Deuterium/Lithium plasma onto Uranium Pellet
  – Careful design of the radial density profile, annular stages, and shock waves may stabilize annular plasma shells that could be collapsed onto a uranium pellet
Forward Work

• Ongoing review of past experiments and analysis
  – Continued maturation of concepts

• Modeling of targets and compression using SPFMax
  – SPFMax is a smooth particle fluid magneto hydrodynamic code under development at the University of Alabama in Huntsville (UAH)
  – Results will influence the design of experiments for Charger 1, a 1 TW pulsed power facility at UAH
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References